FRICTION DAMPERS FOR STAY CABLES DYNAMIC STABILITY ON INCHEON BRIDGE

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Abstract: *Incheon Bridge is a major stay cable project designed by CHODAI Co. Ltd. and Seo Yeong. The slenderness of its structure and its location in severe environmental conditions has risen up dynamic issues, especially for the stay cables. Due to the proven performance of friction damping devices, this technology of damper has been selected to control the stay cable vibrations. This article aims to present the back ground of the design the friction dampers developed by the company VSL, equipping the stay cables of Incheon Bridge.*

Keywords: stay cable, cable vibration, friction damper

1. INCHEON BRIDGE

Ambitious structure

With a main span of 800m, the Incheon Stay Cable Bridge is constituted of a box girder deck wider than 30m, supported with 104 pairs stay cables made of parallel wires. It is the fifth longest stay cable bridge in the w orld in terms of main length. The bridge crosses a navigational channel with a width of 625.5m and a clearance of 74m height (Yang, Ahn, & Kim, 2007).

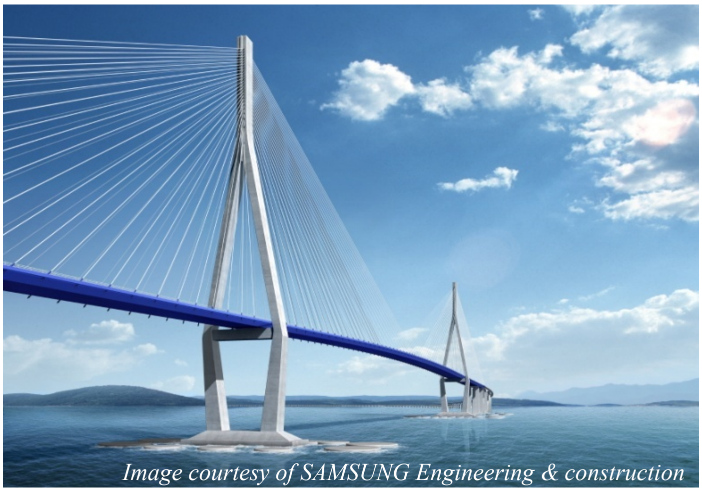


Figure 1 : Artist view of Incheon Bridge

Severe dynamic loading

The untypical slenderness for the Incheon Bridge and its location near the sea has made mandatory the involvement of an expert office for the aerodynamic analysis of the bridge stay cables[1].
As a conclusion of the expert analysis, a damping ratio of 0.5% added to the cables, covers all aerodynamic issues such as dry inclined galloping, vortex shedding, rain and wind induced vibration, etc... In addition to this requirement, VSL has proposed to apply a safety ratio of 1.2 to this specified damping, increasing this nominal value to 0.6% (Yang, Ahn, & Kim, 2007).

Choice of damping device

Technical points of view are prevailing to determine the choice of damping device for such long cables. By inquiring both aspects of durability and performance, the friction damping technology was preferred for the long cables (Yang, Ahn, & Kim, 2007). Even though the durability is an inherent quality of friction damper technology, this has been ascertained by monitoring on severe environment and during maintenance operation on existing bridge such as Uddevalla Bridge-Sweden (Bournand & Crigler, 2005).
Performance of friction dampers is not only demonstrated by theoretical predictions, but full-scale tests have shown that these theoretical performances are either well reproduced or even exceeded[2].

2. FRICTION DAMPER

Principle

A prestressed contact between two specific friction partners located at the interface between a moving structure (cable) and an assumed to be fixed support dissipates the mechanical energy mobilized in the relative movement between these two substructures. Consequently the vibrations are damped until a certain point called threshold amplitude of vibration. The key point for the friction damper design is to create such interface which would dissipate the maximum of mechanical energy while keeping the threshold amplitude below a specified value acceptable for the structure in term of fatigue, and user comfort (RDT, 2005).

[1] Flint & Niell Partnership, Incheon Bridge Project – Cable Damping Review, October 2006
[2] VSL Friction Damper performance measurement on existing bridges: Uddevalla Bridge, (test conducted by NGI July 2000) - Kap Shui Mun Bridge, (test conducted by Hong Kong highway Authority, May 2006). Full-scale performance measurements on laboratories: Tongji University (March 2004) – Korean Highway Corporation (June 2006) (Ahn, Park, Lee, & Park, 2007)

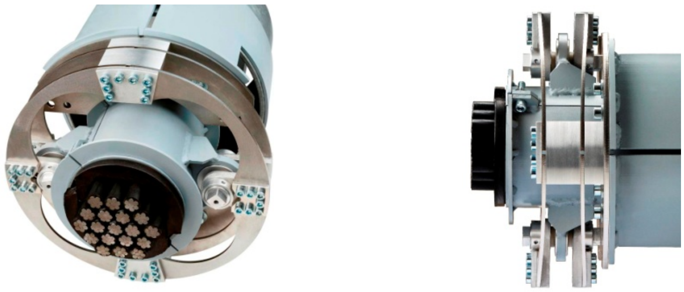


Figure 1 : Typical VSL friction damper

Friction behaviour

The type of friction damper used for Incheon bridge project, developed by VSL presents a behaviour law that can be modelled with the exact friction law of Coulomb.

$$f = F_d \frac{v_r}{|v_r|} \qquad (1)$$

Indeed, friction materials have been chosen to suppress adhesion effects that might induce the so called “stick-slip” phenomenon.

Global behaviour

As it is presented in the chapter 0, the friction damper provides an amplitude dependent damping. The typical relationship between the added damping ratio and the vibration amplitude is presented as follows[3]:

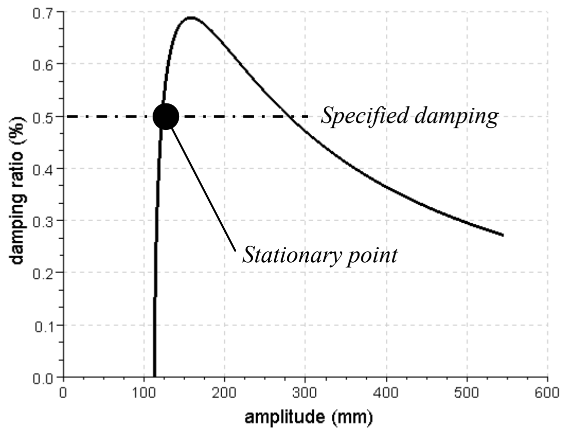


Figure 2 : Modal characteristics

Movement of the cable with amplitude smaller than a hundred millimetres[4] cannot induce at the damper point a deviation force sufficiently high to make it moving. For such small amplitude, the damper remains blocked as it is shown on the Figure 2. Once the vibration increases more, the damper is activated and provides a damping to the cable sufficient to dissipate all introduced energy by the wind or else. The cable movement is stabilised to maximum amplitude corresponding to the stationary point defined in the Figure 2 (Kovacs, Strommen, & Hjorth-Hansen, 1999).

[3] Based on Cable C52 parameters, first mode of vibration
[4] Corresponding to cable length divided by 3400, as per required by the project specifications (Yang, Ahn, & Kim, 2007).

3. DYNAMIC BEHAVIOUR OF A CABLE EQUIPPED WITH A FRICTION DAMPER

Stay cable model

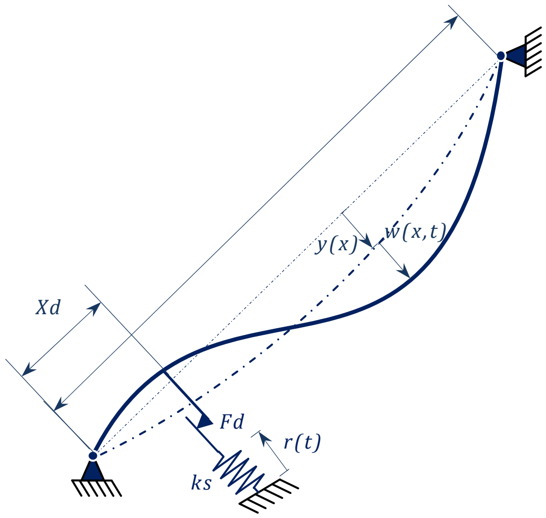


Figure 3 : Schematic model for the stay cable

To determine the damping added to the cable by the friction damper, a research of modal solutions of the typical cable dynamic behaviour equation system is proposed. The dynamic system is applicable for vertical cable movements, since it includes sag effect (Irvine, 1981):

$$\begin{cases} w'' + f_d \delta(x - x_d) \frac{(\dot{w} - \dot{r})}{|\dot{w} - \dot{r}|} - \pi^2 \ddot{w} + \lambda^2 \int_0^1 w.dx \\ \ddot{r} + \left(\frac{\omega_s}{\omega_0}\right)^2 r + \frac{1}{\pi^2} \frac{m}{m_s} f_d \frac{(\dot{w}(x_d) - \dot{r})}{|\dot{w}(x_d) - \dot{r}|} = 0 \end{cases} \quad (2)$$

Where w = dimensionless cable displacement, r = damper support displacement, λ = Irvine parameter, δ = Dirac distribution symbol, fd = dimensionless friction force, x_d = installing ratio, ω_0 and ω_s are the fundamental circular frequencies of the cable and the support, and m and m_s are the masse of the cable and the support. Furthermore, $w' = \partial w / \partial x$ and $\dot{w} = \partial w / \partial t$.

Computation

The computation is performed using a Ritz-Galerkin method (Sulekh, 1990). The projection base is built from the solution of the homogeneous equation taken from (2) and deleting the damping force:

$$\pi^2 \ddot{w} - w'' + \lambda^2 \int_0^1 w.dx = 0 \quad (3)$$

The equation (3) contains the term associated to the sag effect (Cremona, 1997). It leads to the modal deformations as expressed in (4) for the anti-symmetrical modes, and (5) for the symmetrical modes.

$$\varphi_i(x) = \sin(2i\pi x) \quad (4)$$

$$\varphi_k(x) = \left(1 - \cos kx - \tan\frac{k}{2} \sin kx\right) \frac{\cos\frac{k}{2}}{\cos\frac{k}{2} - 1} \quad (5)$$

Where k is solution of the following equation:

$$\tan\frac{k}{2} = \frac{k}{2} - \frac{4}{\lambda^2}\left(\frac{k}{2}\right)^3 \quad (6)$$

The damper induces an inflection point in the cable deformation. It is shown, that the introduction of an additional shape corresponding to the unit static deformation of the cable induced by a force applied at the damper location, increases considerably the computation speed (Johnson, Backer, Spencer, & Fujino, 2000). The shape of the static deflection, takes into account the sag effect (Johnson, Christenson, & Spencer, 2003):

$$\varphi_s(x) = \frac{12+\lambda^2}{12+\lambda^2-3\lambda^2 x_d(1-x_d)} \begin{pmatrix} \frac{x}{x_d} - \frac{3\lambda^2 x(1-x)}{12+\lambda^2} \, if \; x < x_d \\ \frac{1-x}{1-x_d} - \frac{3\lambda^2 x(1-x)}{12+\lambda^2} \, if \; x > x_d \end{pmatrix} \quad (7)$$

The family of functions given by the expressions (4) and (5), completed by the function given in the equation (7), constitute the projection base for the research of solutions of the equation system.

Linearization

The equation (2) is not linear due to the expression of the friction damper loading. The damper reaction is thus linearized by considering the first Fourier transform of the force expression during a periodic movement (Kovacs, Strommen, & Hjorth-Hansen, 1999) - (Main & Jones, 2002):

$$\frac{1}{|\dot{w}(Xd)-t|} \approx \frac{4}{\omega\pi(\Delta-R)} \quad (8)$$

(Δ-R) = considered damper dimensionless amplitude of relative displacement of the damper to its support, at the given step of computation, ω = dimensionless circular frequency of the considered mode of vibration.

Research of eigenmode characteristics

On the basis of the presented space of solution research, the dynamic system can be rewritten as a matrix equation as follows:

$$\boldsymbol{M}\ddot{\boldsymbol{w}} + \boldsymbol{C}\dot{\boldsymbol{w}} + \boldsymbol{K}\boldsymbol{w} = 0 \quad (9)$$

The equation (9) is rewritten in the shape of a first order differential system as follows:

$$\boldsymbol{A}\boldsymbol{Y} = \dot{\boldsymbol{Y}} \quad (10)$$

With:

$$\boldsymbol{A} = \begin{pmatrix} \boldsymbol{0} & \boldsymbol{I} \\ -\boldsymbol{M}^{-1}\boldsymbol{C} & -\boldsymbol{M}^{-1}\boldsymbol{K} \end{pmatrix} \text{ And } \boldsymbol{Y} = \begin{pmatrix} \boldsymbol{w} \\ \dot{\boldsymbol{w}} \end{pmatrix} \quad (11)$$

w is the vector of generalized displacements.

The value of the eigenmode frequencies and damping is determined after the spectrum $[\lambda_i]$ calculation of the matrix ***A***, for each considered damper displacement.

$$\begin{cases} \omega_i = \omega_0 |\lambda_i| \\ \xi_i = -\frac{\mathrm{Real}(\lambda_i)}{|\lambda_i|} \end{cases} \quad (12)$$

The eigenmode shape $\mathbf{Y}_i$ is determined by the calculation of the kernel of $(\boldsymbol{A} - \omega_i \boldsymbol{I})$.

The cable amplitude of vibration associated to the considered damper displacement is finally determined after scaling the eigenmode amplitude in respect of the damper displacement relatively to the support (Hjorth-Hansen, Strommen, Myrvoll, Hansvold, & Ronnebrand, 2001).

Numerical application

The subsequent results of the computation previously presented according to the hypotheses deducted from the characteristics of the longest cable of Incheon Bridge, are given for the vertical mode of vibration[5].

Cable C52

Chord length	416.8	m
Average service tension	4832.6	kN
Distributed mass	94.9	kg/m
Nominal cross section	115.84	cm^2
Inclination	20.8	degree
Damper position from deck anchorage	7.72	m
Damper friction force	4400	N

[5] Data provided by KODA Development Co., Ltd.

The resulted damping ratio is presented as a function of the mode amplitude:

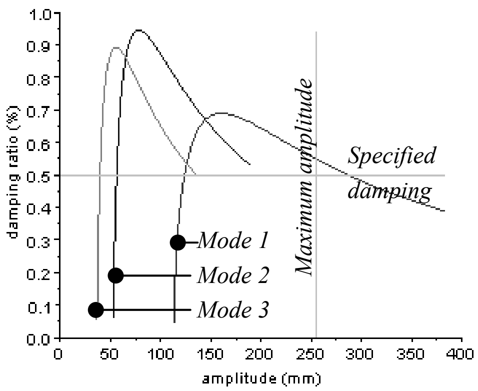


Figure 4 : Damping ratio versus amplitude

The curves highlight the principle of functioning of the friction damper: small vibration, below 100mm for the first mode, inducing no fatigue effects on the stay cable component are not damped, but just filtered by the blocked damper. If vibrations amplitude starts to increase, the damper is activated and it provides almost immediately its maximum performance. The Figure 5 shows the very limited damper movement sufficient to damp the cable movement.

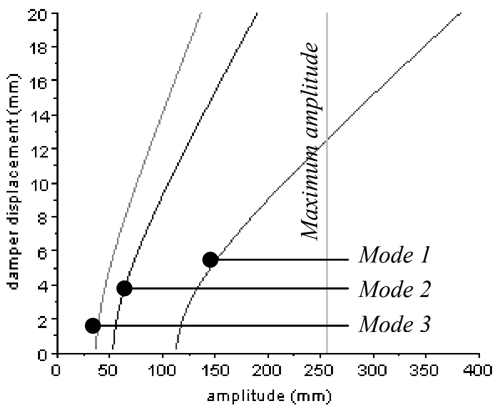


Figure 5 : Damper displacement versus cable amplitude

4. DETAIL DESIGN

Consideration for detailing

A damping device shall be design in order to provide the specified performance for the service conditions of the bridge. Therefore, effects of cable tension variation and static deformations due to transverse loading on the cable shall be addressed properly, in order not to induce alteration on the damping performances.
The tension variation of the stay cable induces two types of movement of the cable at the damper location: A transverse displacement due to the sag variation, and a longitudinal displacement due to the cable elongation. As having no hinge connection to its support, the friction damper accommodates such cable static movement either by the elasticity of its blades and the width of the sliding plate. The Figure 7 and the Figure 8 show the principle of the cable movement accommodation.
The blades can be considered as springs, deflected in order to generate the friction force by acting on both top and bottom side of the sliding plate:
The next schemes illustrate the functioning of the compression force introduction under potential near to static movement.

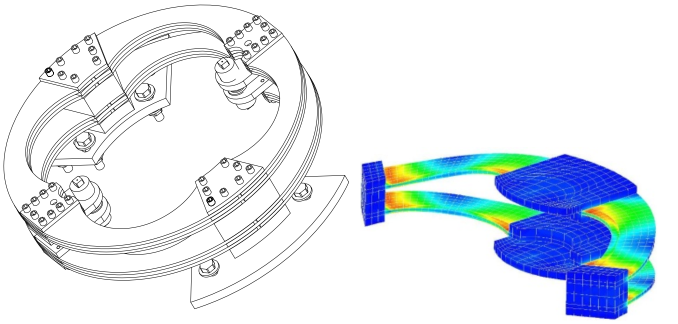


Figure 6 : Spring blade principle

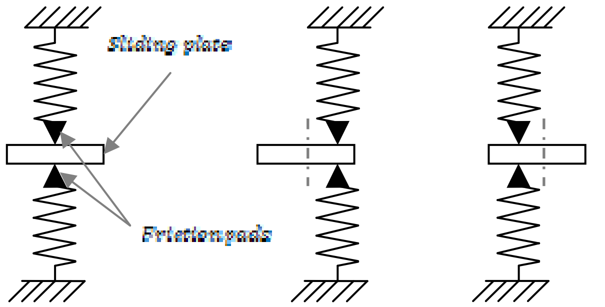
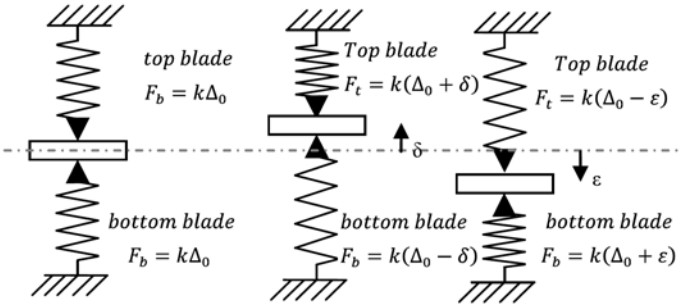


Figure 7 : Accommodation of transverse displacement



resultant : $F_d = \mu(F_t + F_b) = \mathbf{2\mu k\Delta_0}$

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Figure 8 : Accommodation of longitudinal movement

As it is seen on the Figure 8, the resultant force is independent from the longitudinal blade displacement.

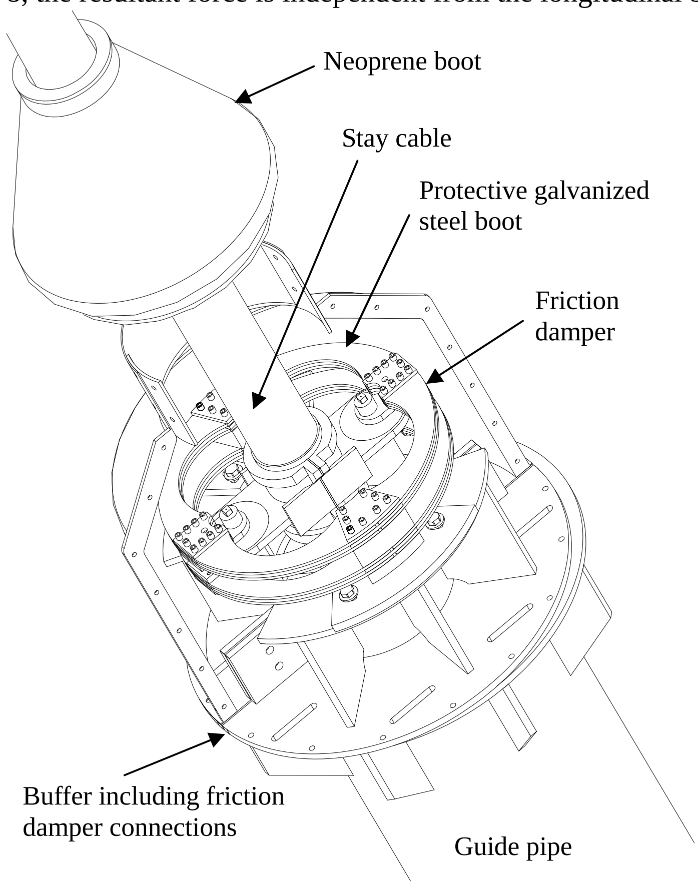

Figure 9 : General assembly of VSL friction damper for Incheon Bridge

5. CONCLUSION

Despite the design challenge due to the complexity of friction dampers, such devices present characteristics that make them very suitable to control the stability of long span stay cable bridges.

REFERENCES

[1] Ahn, S.-S., Park, J.-H., Lee, S.-H., & Park, C.-M. (2007). Behaviour Comparison of Cable Dampers by Full Scale Experiment. *Seventh International Symposium on Cable Dynamics* (pp. 379-384). Vienna: A.I.M.

[2] Bournand, Y., & Crigler, J. (2005). The VSL Friction Damper or Cable Stayed Bridges.Some Results from Maintenance and Testing on Long Cables. *Sixth International Symposium on Cable Dynamics* (pp. 199-204). Charleston, South Carolina: A.I.M.

[3] Cremona, C. (1997, vol. 1). Courbe universelle pour le dimensionnement d'amortisseurs en pied de haubans. *Revue française de génie civil* , pp. 137-159.

[4] Hjorth-Hansen, E., Strommen, E., Myrvoll, F., Hansvold, C., & Ronnebrand, R. (2001). Performance of a Friction Damping Device for the Cables on Uddevalla Cable-Stayed Bridge. *fourth International Symposium on Cable Dynamics* (pp. 179-186). Montreal: A.I.M.

[5] Irvine, M. (1981). *Cable Structures.* Cambridge: Press of the MIT.

[6] Johnson, E. A., Christenson, R. E., & Spencer, J. B. (2003). Semiactive Damping of Cables with Sag. *Computer-Aided Civil and Infrastructure Engineering* , 132-146.

[7] Johnson, E., Backer, G., Spencer, B., & Fujino, Y. (2000). Mitigating Stay Cable Oscillation using Semiactive Damping. *Smart Structures and Material 2000* (pp. 207-216). SPIE vol. 3988.

[8] Kovacs, I. (October 1982). Zur Frage der Seilschwingungen und der Seildampfung. *Die Bautechnik* , S. 325-332.

[9] Kovacs, I., Strommen, E., & Hjorth-Hansen, E. (1999). Damping Devices Against Cable Oscillations on Sunningesund Bridge. *Third International Symposium on Cable Dynamics* (pp. 145-150). Trondheim: A.I.M.

[10] Main, J. A., & Jones, N. P. (2002, October). Free Vibrations of Taut Cable with Attached Damper. *Journal of engineering mechanics* , pp. 1072-1081.

[11] NGI. (2000). *Uddevallabron - Performance Testing, Field Measurements.*

[12] RDT. (2005). *Wind induced Vibration of Stay Cables.* Jefferson: Missouri Department of Transportation; Reaserch Development and Technology.

[13] Sulekh, A. (1990). Non-Dimmensionalized Curves for Modal Damping in Stay Cables with Viscous Dampers. *Master Thesis* . Tokyo, Japan: Department of Civil Engineering, University of Tokyo.

[14] Yang, J.-H., Ahn, S.-S., & Kim, H.-K. (2007). Design of Cable Dampers and Buffers in Incheon Cable-Stayed Bridge. *Seventh International Symposium on Cable Dynamics* (pp. 385-392). Vienna: A.I.M. .